Hot And Cool: Bridging Gaps in Massive Star Evolution
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Constraining the evolution of red supergiants with the integrated light of star clusters.

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Abstract. The integrated properties of young star clusters are subject to large cluster-to-cluster variations because they depend directly on small numbers of bright stars. At ages at which red supergiants are expected to exist, these luminous but rare stars can be blamed for most of the variations. If unresolved clusters are to be used to constrain red supergiant models, methods must be developed that take these stochastic fluctuations into account. We discuss prospects and open issues in this field, based on recent work on high mass clusters in M 82, and on first experiments towards a Bayesian study of cluster populations.

1. Introduction

Stellar astrophysics has a long tradition of using star clusters to test and improve evolutionary models : with small internal spreads in age and metallicity, clusters do indeed provide an extraordinary testbed. It is natural to consider using young clusters when studying the evolution and the properties of massive stars. In this contribution, we focus on the red supergiant phase of the evolution of relatively massive stars (typically 7–25 $M_\odot$), i.e. cluster ages of about 8 to 60 Myr. We also limit the discussion to clusters that can not be resolved into individual stars.

Red supergiants (RSGs) are intrinsically rare objects, as a combined result of the stellar Initial Mass Function (IMF) and of the short duration of the relevant evolutionary phase. At cluster ages of 10 to 30 Myr, their expectation numbers are of order one for total cluster masses of order $10^4\,M_\odot$ for a standard IMF with a lower mass cut-off of $0.1\,M_\odot$ (see Tab. 3 of Lançon et al. 2008). Thus, individual clusters of $10^4\,M_\odot$ might host zero, one, two or a few red supergiants, which translates into multimodal probability distributions for colours such as $(V-K)$. It takes clusters of several $10^6\,M_\odot$ to reduce random variations in the K band flux and in $(V-K)$ to less than about 5 %, in which case flux and colour distributions are also single peaked and gaussian approximations become tolerable. Interesting work on flux and colour distributions at various cluster ages include Barbaro & Bertelli (1977), Girardi & Bica (1993), Lançon & Mouhcine (2000), Bruzual (2001), Cerviño et al. (2002, 2006).

The effects of changes in stellar model assumptions can be tested by direct comparisons with the integrated properties of individual star clusters only if they are larger than the spread resulting from the above-mentioned small numbers of luminous stars, the so-called "stochastic fluctuations".

As discussed in several contributions to this meeting, models relevant to the red supergiant phase of evolution remain particularly uncertain. This is seen when comparing theoretical stellar spectra with empirical spectra of luminous cool stars (Lançon et al. 2007), or when using different sets of evolutionary tracks in population synthesis calculations. For instance, González Delgado et al. (2005) compare synthetic spectra of Single Stellar Populations (SSP) based on the tracks of the Geneva group and the Padova group, respectively (Schaller et al. 1992, Girardi et al. 2000); and Vázquez et al. (2007) consider tracks with and without inital rotation (Meynet & Maeder 2005). The effects of currently acceptable changes in model assumptions are large enough that we can expect constraints from the integrated light of star clusters despite the stochastic fluctuations. Possibilities have not yet been exploited fully, because replacing evolutionary tracks or stellar spectral libraries in population synthesis models is not as trivial as one might wish, and because probabilistic methods for tackling low mass clusters are still under development. First results highlight prospects and difficulties.

2. Individual massive star clusters

Massive young star clusters are found in actively star forming galaxies, where the total number of clusters formed is large enough for the upper end of the cluster mass function to be populated. An example is M 82. Five clusters more massive than $5\,10^5\,M_\odot$ in M 82 were studied by Lançon et al. (2008; L08 hereafter), based on extended near-IR spectra ($0.8-2.4\,\mu$m; $\lambda/\delta\lambda \sim 1000$) and pre-existing optical data. All these clusters have near-IR spectral signatures that immediately suggest a strong contribution from red supergiants. This is a common and expected property of starburst populations.

Using a population synthesis tool based on Pegase (Fioc & Rocca-Volmerange 1997), with the evolutionary tracks of Bressan et al. (1993) and a new empirical near-IR library, L08 showed that it was possible to obtain very good fits to the near-IR spectra of the star clusters in M82. The derived near-IR ages lie between 9 and 40 Myr, i.e. in the age range where the contributions of luminous red supergiants (class Ia and Iab) are strongest in the models.

However, the near-IR ages do not always agree with the best optical ages in the previous literature. The optical studies most frequently use the spectral region around the Balmer jump, a wavelength range at which red supergiants contribute very little, but which is affected by light from stars on the blue loops of evolutionary tracks. At the ages derived from optical studies for three clusters, the red supergiant features in the model spectra of L08 tend to be too weak.

What does this tell us about red supergiants models?

The spectra of massive clusters in M82 favour models that give luminous red supergiants a strong weight in the near-IR light. This can be achieved in various ways, among which:

– longer lifetimes in the red phases of evolution;

– higher assigned gravities for the library stars of class Ia and Iab (with higher assigned gravities, these spectra contribute to the emission of SSPs over a wider range of ages);

– changes in the adopted bolometric corrections.

In order to finalise this study and determine which set of evolutionary models and model atmosphere inputs are best able to reproduce reality in M 82, it will be necessary to obtain even better spectra. At spectral resolutions of about 1000, it is critical to use optical and near-IR data jointly, otherwise the problem is underconstrained. Observational apertures must be very precisely matched. Indeed, high resolution images of the clusters in M 82 show that there is significant substucture on the scale of a single cluster, with extinction lanes covering parts of them, and contaminating nebular or stellar sources on very close lines of sight (e.g. Bastian et al. 2007). It is hoped that instruments such as the upcoming ESO/VLT/Xshooter will be available for observational programmes of this type in Southern Hemisphere galaxies.

Of course, one must keep in mind that the most compact massive star clusters might not be the best templates for stellar evolution as a whole. With thousands of stars within each cubic parsec, their red supergiants could be affected by neighbourhood effects; interacting binaries and multiple systems may be more frequent than elsewhere (see the discussion focused on AGB stars by Gallagher & Smith, 2007, and references therein). Also, massive clusters might not all contain simple coeval stellar populations. Self-enrichment could occur over timescales that are under debate. Globular clusters, for instance, display abundance patterns that are attributed to short-lived massive stars by some authors (Decressin et al. 2007), to longer-lived intermediate mass stars by others (D'Ercole et al. 2008). Finally, some clusters may be the results of mergers. The analysis of high quality, extended spectra of massive clusters with standard models will show whether additional physical phenomena such as these need to be taken into account. We suspect that the effects of non-instantaneous star formation and of binarity on the integrated properties may be testable despite the stochastic fluctuations.

3. Clusters of more common total masses

Without a good estimate of age and metallicity, it is difficult to use the light of a cluster to constrain the underlying stellar models. Methods that explicitly deal with stochastic fluctuations when estimating the properties (mass, age, metallicity) of small or intermediate mass clusters from their integrated fluxes are in their infancy. The approach we are currently developing is a Bayesian one, which aims at determining the age, metallicity and mass probability distribution of observed clusters, based on their broad band fluxes. Mass (or an analog of mass, such as the total number of stars above $0.1\,M_{\odot}$) is a variable that comes into the problem because (i) the colour probability distributions of clusters of a given age and metallicity depend strongly on mass, and (ii) even if dynamical masses are available, the uncertainties about the lower end of the IMF make the translation into the relevant average number of bright stars uncertain.

We have started a campaign of Monte-Carlo (MC) simulations, that we will use as a database for establishing the joint probability distributions of mass, metallicity and age of clusters with given photometric properties (Fouesneau et al., in preparation). A first simple example is given in Figure 1. It is seen that even when five absolute fluxes are available across the spectrum, the range of possible ages remains broad when dealing with clusters of 10^3 stars. Varying

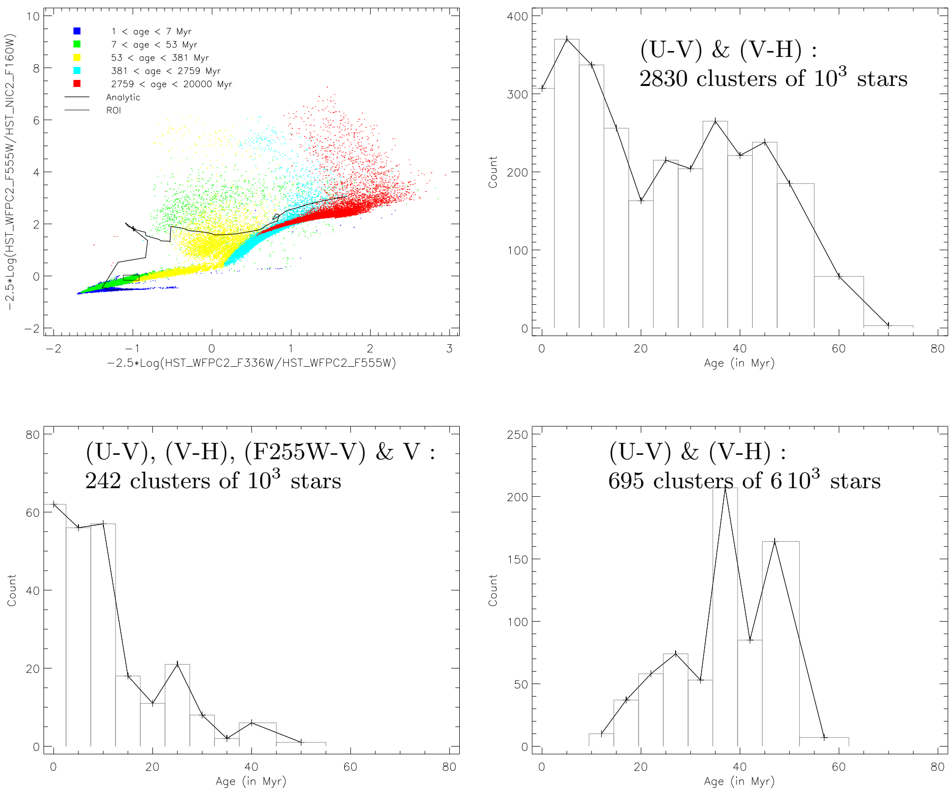

Figure 1. **Top left:** HST colors of 69000 star clusters each containing 10^3 stars. The colours shown combine fluxes in F336W (U) and F555W (V) of WFPC2, and F160W (H) of NICMOS2. Ages are distributed uniformly on a logarithmic scale between 1 Myr and 20 Gyr. The solid line shows the evolution of the average colours (average over an infinite number of clusters of the same age) with age. Solar metallicity is assumed. The box near coordinates [-1;0] surrounds the locus of one particular 8 Myr old cluster, and illustrates 0.1 magnitude error bars. **Top right:** Age distribution of the clusters with (U-V) and (V-H) colours within the above-mentioned error box (2830 clusters out of 69000). **Bottom left:** Age distribution of the clusters found when the selection includes one more ultraviolet band and the absolute V magnitude (242 clusters out of 69000). **Bottom right:** Age distribution obtained with a selection as in the upper right pannel, but using a database of clusters that all contain $6\,10^3$ stars instead of 10^3 (695 clusters out of 69000).
[NB: TOP LEFT PANNEL APPEARS PROPERLY ONLY IN THE POSTSCRIPT VERSION, NOT IN THE PDF VERSION DOWNLOADED FROM ARXIV.ORG]

the assumed number of stars changes the results significantly, even when only colours and no absolute fluxes are used. We are in the process of exploring the effects of metallicity and extinction.

The simulations are currently being extended. Clearly, the final age probability distribution obtained for an individual cluster will depend on the distribution of ages, metallicities and total masses in the MC database: these are the priors of the Bayesian approach. The condition that colours should be within a rigid error box (as in Fig. 1) can be replaced with a continuous weighting scheme under the assumption that observational errors are gaussian. Globally, the method we are developing is a close analog of the one introduced by Kauffmann et al. (2003) for the study of star formation histories in the Sloan Digital Sky Survey galaxies, except that the variety of observable properties has completely different origins in both contexts.

The above approach is initially designed for the study of populations of star clusters in the context of a host galaxy. What can we learn here about red supergiants? Our current numerical explorations leave us with the impression that it will be difficult to constrain red supergiant theory with clusters of 10^3 solar masses, while it should become possible with several 10^4 solar masses. In order to make us reject a stellar model, the colours of a cluster have to lie in a region of the multi-dimensional colour-magnitude diagram that is not populated (significantly) in spite of the stochastic fluctuations. The comparison of synthetic colour-magnitude diagrams constructed with MC simulations based on different stellar assumptions shall tell us which colours and fluxes are most discriminant.

As an alternative approach, one might attempt to fit the colours or spectrum of a low mass cluster with a combination of (i) the synthetic spectrum of a well populated lower IMF (up to near the turn-off) and (ii) the spectra of a library of luminous stars. In some cases, it should be possible to obtain strong constraints on the individual nature of the handful of most luminous stars. However, this will work best when the red supergiants are very few, in which case the cluster as a whole will not be much brighter than a single red supergiant star. Stochasticity will be important even for stars near the turn-off, and the constraints on stellar evolution will probably not be much more stringent than those obtained from field stars in the host galaxy. It would be worth testing these statements with simulations.

4. Conclusion

Red supergiants are responsible for large stochastic fluctuations in the integrated energy distribution of all but the most massive young star clusters. These massive clusters provide useful tests for stellar evolution models, and should be exploited using high signal-to-noise, co-spatial spectra covering UV to optical wavelengths. New tools that deal with stochastic fluctuations explicitely need to be developed further, if clusters of more normal masses are to provide robust constraints on red supergiant models. We hope to report progress in this area soon.

References

Barbaro, C. & Bertelli, C. 1977, A&A 54, 243
Bastian, N., Konstantopoulos, I., Smith, L.J., et al. 2007, MNRAS 379, 1333
Bressan, A., Fagotto, F., Bertellli, G. & Chiosi, C. 1993, A&AS 100, 647
Bruzual, G.A. 2001, in Extragalactic Star Clusters, IAU Symp. Ser. 207, 616
Cerviño, M., Valls-Gabaud, D., Luridiana, V., Mas-Hesse, J.M. 2002, A&A 381, 51
Cerviño, M., & Luridiana, V. 2006, A&A 451, 475
Decressin, T., Charbonnel, C., Meynet, G. 2007, A&A 475, 859
D'Ercole, A., Vesperini, E., D'Antona, F. et al. 2008, MNRAS 391, 825
Fioc, M. & Rocca-Volmerange, B. 1997, A&A 326, 950
Gallagher, J.S., III & Smith, L.J. 2007, in Why Galaxies Care About AGB Stars, Ed. F. Kerschbaum, C. Charbonnel, R.F. Wing, ASP Conf. Ser. 378, 370
Girardi, L., & Bica, E. 1993, A&A 274, 279
Girardi, L., Bressan, A., Bertelli, G., Chiosi, C. 2000, A&AS 131, 371
González Delgado, R.M., Cerviño, M., Martins, L.P., Leitherer, C., Hauschildt, P.H. 2005, MNRAS 357, 945
Kauffmann, G., Heckmann, T.M., White, S.D.M. et al. 2003, MNRAS 341, 33
Lançon, A., & Mouhcine, M. 2000, in Massive Stellar Clusters, ed. A. Lançon, & C.M. Boily, ASP Conf. Ser. 211, 34 (corrected equation: arXiv:astro-ph/0003451v2)
Lançon, A., Hauschildt, P., Ladjal, D. & Mouhcine, M., 2007, A&A, 468, 205
Lançon, A., Gallagher, J.S., III, Mouhcine, M., Smith, L.J., Ladjal, D. & de Grijs, R. 2008, A&A 486, 165
Meynet, G. & Maeder, A. 2005, A&A 429, 581
Schaller, G., Schaerer, D., Meynet, G., Maeder, A. 1992, A&AS 96, 269
Vázquez, G.A., Leitherer, C., Schaerer, D., Meynet, G., Maeder, A. 2007, ApJ 663, 995